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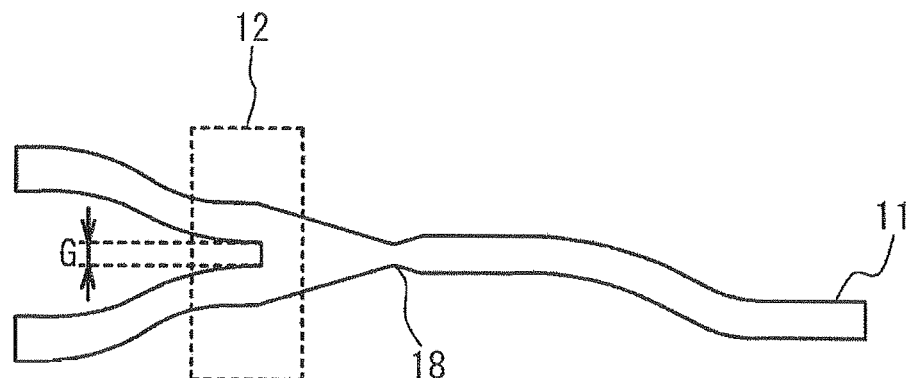
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(54) **Curved optical waveguide**

(57) An optical waveguide formed in an electro-optical substrate includes a curved waveguide (11) having a first end and a second end and a branch portion (12) that is coupled to the second end of the curved waveguide, wherein the curved waveguide (11) comprises a low refraction index portion (18) having an effective refraction index that is lower than that of the rest of the curved waveguide, the low refraction index portion (18) being provided between the first end and the second end of the curved waveguide (11).

prises a low refraction index portion (18) having an effective refraction index that is lower than that of the rest of the curved waveguide, the low refraction index portion (18) being provided between the first end and the second end of the curved waveguide (11).

FIG. 4B



Description

FIELD

[0001] A certain aspect of embodiments described herein relates to an optical waveguide, an optical modulator and an optical coupler.

BACKGROUND

[0002] An optical waveguide device using an electrooptical crystal such as a LiNbO_3 (LN) substrate, a LiTaO_3 substrate or the like is being developed. These optical waveguide devices may be formed through processes of providing an electrode near an optical waveguide after forming the optical waveguide by forming a metal film such as Ti on a part of a crystal substrate and thermally diffusing the metal film or by proton-exchanging in benzoic acid after patterning. Japanese Patent Application Publication No. 05-53086 discloses a Mach-Zehnder optical modulator as the optical waveguide device.

[0003] The Mach-Zehnder optical modulator may have a Y-shaped branch portion after a curved waveguide. In the structure, the branch portion receives a mode shifted in the curved waveguide. Thus, a branching ratio may be shifted from 50%. This may result in degradation of an extinction ratio of the Mach-Zehnder. A straight waveguide may be provided before the branch portion in order to move the branching ratio closer to 50%. However, in this case, there is a problem that the optical modulator grows in size.

SUMMARY

[0004] The present invention has been made in view of those circumstances, and an object thereof is to provide an optical waveguide, an optical modulator, and an optical coupler that may be downsized and may restrain degradation of a branching ratio.

[0005] According to an aspect of the present invention, there is provided an optical waveguide formed in a substrate including: a curved waveguide; and a branch portion that is coupled to the curved waveguide and branches, wherein a low refraction index portion having an effective refraction index that is lower than that of a start point of the curved waveguide on an opposite side of the branch portion is provided in a waveguide extending from the start point of the curved waveguide to the branch portion.

[0006] According to another aspect of the present invention, there is provided an optical modulator of Mach-Zehnder type including: a first branch portion of light-inputting side; and a second branch portion of light-outputting side, wherein: at least one of the first branch portion and the second branch portion includes an optical waveguide formed in a substrate comprising a curved waveguide and a branch portion that is coupled to the

curved waveguide and branches; a low refraction index portion having an effective refraction index that is lower than that of a start point of the curved waveguide on an opposite side of the branch portion is provided in a waveguide extending from the start point of the curved waveguide to the branch portion; and the substrate has electrooptical effect.

[0007] According to another aspect of the present invention, there is provided an optical coupler including: an inputting waveguide; and an outputting waveguide, wherein: at least one of the inputting waveguide and the outputting waveguide includes an optical waveguide formed in a substrate comprising a curved waveguide and a branch portion that is coupled to the curved waveguide and branches; and a low refraction index portion having an effective refraction index that is lower than that of a start point of the curved waveguide on an opposite side of the branch portion is provided in a waveguide extending from the start point of the curved waveguide to the branch portion.

BRIEF DESCRIPTION OF DRAWINGS

[0008]

FIG. 1A illustrates a schematic plane view of a Mach-Zehnder type optical modulator in accordance with a first embodiment;

FIG. 1B illustrates a cross sectional view taken along a line A-A of FIG. 1A;

FIG. 2A illustrates a comparative embodiment;

FIG. 2B illustrates a first embodiment,

FIG. 3A illustrates a spectrum of a branching ratio in a case where a width of a start point of a small width portion is changed in a structure of FIG. 2B;

FIG. 3B illustrates an insertion loss (dB);

FIG. 3C illustrates wavelength dependency;

FIG. 3D illustrates a relation between a curvature radius and an excessive loss of a curved waveguide;

FIG. 4A illustrates a modified embodiment 1-1;

FIG. 4B illustrates another example of the modified embodiment 1-1;

FIG. 4C illustrates a modified embodiment 1-2;

FIG. 5A illustrates a modified embodiment 1-3;

FIG. 5B illustrates a modified embodiment 1-4;

FIG. 6A illustrates a modified embodiment 1-5;

FIG. 6B illustrates a modified embodiment 1-6;

FIG. 6C illustrates a modified embodiment 1-7;

FIG. 7A illustrates a schematic plane view of a QPSK optical modulator in accordance with a second embodiment;

FIG. 7B illustrates an enlarged view of branch portions and a curved waveguide;

FIG. 8 illustrates another example of branch portions and a curved waveguide;

FIG. 9A through FIG. 9C illustrate an optical coupler;

FIG. 10A through FIG. 10C illustrate an adjusting method of an effective refraction index;

FIG. 11 illustrates a cross sectional view of a silicon waveguide; and

FIG. 12 illustrates a block diagram of an optical transmitter in accordance with a fourth embodiment.

DESCRIPTION OF EMBODIMENTS

[0009] The following is a description of embodiments of the present invention, with reference to the accompanying drawings.

[a] First Embodiment

[0010] FIG. 1A illustrates a schematic plane view of a Mach-Zehnder type optical modulator 100 in accordance with a first embodiment. FIG. 1B illustrates a cross sectional view taken along a line A-A of FIG. 1A. As illustrated in FIG. 1A and FIG. 1B, the optical modulator 100 has a substrate 10 including a curved waveguide 11, a branch portion 12, intermediate waveguides 13 and 14, a combine portion 15, and a curved waveguide 16. The substrate 10 is an electrooptical substrate including an electrooptical crystal such as LiNbO_3 (LN) substrate or LiTaO_3 substrate.

[0011] The curved waveguide 11, the branch portion 12, the intermediate waveguides 13 and 14, the combine portion 15 and the curved waveguide 16 are formed through thermal diffusion of a metal such as Ti into the substrate 10. A first end of the curved waveguide 11 acts as an inputting end of the optical modulator 100. A second end of the curved waveguide 11 is coupled to a first end of the branch portion 12. The branch portion 12 branches toward an opposite side of the curved waveguide 11 through a Y-shaped branch portion. The branched waveguides of the branch portion 12 are coupled to a first end of the intermediate waveguides 13 and 14 respectively. The intermediate waveguides 13 and 14 are arranged in parallel with each other. A second end of the intermediate waveguide 13 and 14 is coupled to a first end of the curved waveguide 16 through a Y-shaped combine portion of the combine portion 15. A second end of the curved waveguide 16 acts as an outputting portion of the optical modulator 100. With the structure, the curved waveguide 11, the branch portion 12, the intermediate waveguides 13 and 14, the combine portion 15 and the curved waveguide 16 form an optical waveguide.

[0012] As illustrated in FIG. 1B, there is provided a buffer layer 30 on a face of the substrate 10 on the optical waveguide side. Thus, the optical waveguide is covered with the buffer layer 30. The buffer layer 30 is provided to prevent absorption of a light propagating in the optical waveguide into an electrode described later. The buffer layer 30 is, for example, made of SiO_2 or the like having a thickness of $0.2\ \mu\text{m}$ to $2\ \mu\text{m}$.

[0013] A signal electrode 21 is provided above the intermediate waveguide 13. The buffer layer 30 is located between the intermediate waveguide 31 and the signal electrode 21. A ground electrode 22 is provided above

the intermediate waveguide 14. The buffer layer 30 is located between the intermediate waveguide 14 and the ground electrode 22. Thus, the signal electrode 21 and the ground electrode 22 form a coplanar electrode. Each of the above electrodes is provided directly above the intermediate waveguide in order to use refraction index changing caused by an electrical field in a Z-direction, if a Z-cut substrate is used as the substrate 10.

[0014] When the optical modulator 100 is operated with high speed, a traveling-wave electrode is structured by coupling a dead end of the signal electrode 21 to a dead end of the ground electrode 22 through a resistor, and a microwave signal is applied to the traveling-wave electrode from an inputting side. In this case, refraction index of the intermediate waveguides 13 and 14 changes by $+\Delta n$ or $-\Delta n$ according to the generated electrical field. Thus, a phase difference between the intermediate waveguides 13 and 14 changes, and a Mach-Zehnder interference is established. Accordingly, an intensity-modulated optical signal is output from the second end of the curved waveguide 16. An effective refraction index of the microwave may be controlled by changing a cross section shape of the traveling-wave electrode. High-speed optical responsiveness may be obtained by matching the speed of the optical signal and that of the microwave.

[0015] As illustrated in FIG. 1A, an inputting end and an outputting end of the waveguide (the first end of the curved waveguide 11 and the second end of the curved waveguide 16) are located on approximately center of the optical modulator in a width direction, considering a combination with a fiber. The width direction of the optical modulator 100 corresponds to a vertical direction of a paper of FIG. 1A. On the other hand, in an interaction portion including the intermediate waveguides, an inputting portion and an outputting portion of the electrode are located on one side in the width direction of the optical modulator 100. The inputting portion and the outputting portion of the electrode are a bonding pad or the like. Thus, the intermediate waveguides are located on the other side. With the structure, the width of the optical modulator 100 may be reduced. However, a position of the inputting end and the outputting end of the waveguide is different from that of a waveguide of the interaction portion. So, it is effective that the waveguide is curved into a S-shape with use of the curved waveguides 11 and 16.

[0016] However, if the curved waveguides 11 and 16 are provided, the branch portion 12 is located after the curved waveguide 11. In this case, the branch portion 12 receives a mode shifted in the curved waveguide 11. Thus, the branching ratio may be shifted from 50%. This may result in degradation of the extinction ratio of Mach-Zehnder. So, a long straight waveguide 17 may be provided before the branch portion 12 as illustrated in FIG. 2A. However, with the structure, the optical modulator may grow in size. And, the branching ratio may have wavelength dependency.

[0017] Unequal division of power at the branch portion, a difference of waveguide propagation loss of each path, or the like may cause the degradation of the extinction ratio of Mach-Zehnder. The present inventor has researched carefully from viewpoints of experiment and analysis in order to find a factor. In the experiment, the present inventor has researched an amount of loss in each part of the modulator in detail, and has determined a region causing the degradation of the extinction ratio. The present inventor has repeated designing, experimental-producing, estimating, analyzing or the like of a sample for finding the factor. The present inventor has determined that shifting of the branching ratio of the branch portion is highly possibly a main factor.

[0018] The present inventor has confirmed a theory through an analysis based on the research. The present inventor used a beam propagation method as a waveguide simulation, repeated structuring of a model, setting of an analysis parameter and calculating, and improved analysis accuracy through a feedback from a measured value. Thus, the present inventor has confirmed that the analysis model is adequate. Through analyzing of the analysis result, the present inventor has concluded that the branching ratio of the branch portion is shifted from 50% because the branch portion receives an optical propagation mode having a distribution shifted in the curved waveguide, and the shifted branching ratio is a main factor of the degradation of the extinction ratio.

[0019] Based on the analysis result, the present inventor has researched a designing method for improving the extinction ratio. The present inventor repeated the simulation with variable parameters of the branch portion, and researched influence of each parameter on the extinction ratio. When the straight waveguide is provided before the branch portion, the optical modulator may grow in size and may have the wavelength dependency although the branching ratio gets closer to 50%. Through the research, the present inventor has made a method for reducing an effective refraction index of a waveguide from a start point of the curved waveguide on an opposite side of the branch portion to the branch portion, from a viewpoint of restraining influence of disproportionate of the propagation mode. With the method, the mode shifted in the curved waveguide is not coupled to an asymmetric mode in the waveguide of the branch portion. Thus, the symmetric property of the mode is improved, and the branching ratio may get closer to 50% or may correspond to 50%. The effective refraction index may be changed by changing a cross sectional area of the waveguide, by changing a width or depth of the waveguide, or by changing impurity concentration in the waveguide. In the following description, the effective refraction index is changed by changing the width of the waveguide.

[0020] In an example of FIG. 2B, a small-width portion 18 having relatively small waveguide width is provided at an end of the curved waveguide 11 on the side of the branch portion 12. In concrete, a width at a start point of the curved waveguide 11 on the opposite side of the

branch portion 12 is referred to as "w1". A width of the small-width portion 18 is referred to as "w2". A relation "w1>w2" is satisfied. In the example of FIG. 2B, the width is discontinuously reduced at the start point of the small width portion 18 on the opposite side of the branch portion 12. Thus, the effective refraction index of the small width portion 18 may be reduced by reducing the width. That is, the small width portion 18 acts as a low refraction portion having relatively small effective refraction index.

[0021] There may be possibility that confining of light at a part of a waveguide having relatively small width is degraded and radiation loss may be increased. The radiation loss depends on a wavelength of a light propagating in a waveguide. The longer the wavelength of the propagating light is, the larger the radiation loss is. And so, the present inventor has taken a trade-off with the branching ratio into consideration, and has researched a preferable width of a waveguide for reducing the loss and for improving the branching ratio.

[0022] FIG. 3A illustrates a spectrum of the branching ratio in a case where the width of the start point of the small width portion 18 is changed in the structure of FIG. 2B. FIG. 3B illustrates an insertion loss (dB) of the small width portion 18. The width of the small width portion 18 is 4.5 μm , 6.0 μm , and 7.5 μm . As illustrated in FIG. 3A, the branching ratio of the branch portion 12 is greatly shifted from 50% on the side of long wavelength when the width of the small width portion 18 is large. However, the branching ratio is improved when the width of the small width portion 18 is small. Therefore, the wavelength dependency is improved by reducing the width of the waveguide. As illustrated in FIG. 3B, the width of the waveguide has little influence on the insertion loss, and the branching ratio is improved in the range of FIG. 3B without loss increase.

[0023] A high extinction ratio (for example 25dB or more) is required for a QPSK (Quadrature Phase Shift Keying). For example, a branching ratio of 50% plus minus 5% (within 45% to 55%) is required. The branching ratio is within 45% to 55% in the C-band (1530nm to 1565nm) and in the L-band (1565nm to 1625nm) when the width is 6.0 μm or less in FIG. 3A. It is therefore preferable that the width of the small width portion 18 is 6.0 μm or less. And it is more preferable that the width of the small width portion 18 is 4.5 μm or less.

[0024] There may be a problem of designing when the small width portion 18 is provided. This is because calculation amount of data for calculating drawing points of a photo mask used in a patterning increases greatly when the waveguide is curved and the width is changed. In this case, the drawing requires a large amount of time. Therefore, forming of a pattern and checking require a large amount of time. Further, amount of calculated data is large. When, the amount of calculated data exceeds a limit, the photo mask may not be formed. So, the present inventor has created a method of discretizing the data so that the continuity of the waveguide is maintained to some extent and the amount of calculated data is re-

duced. The present inventor designed a sample, produced the sample experimentally, and estimated the sample. Then, as illustrated in FIG. 3C, a branching ratio having small wavelength dependency has been obtained, and the problem of designing has been solved.

[0025] On the other hand, the confining effect may be degraded and the radiation loss may be increased, when the width of the small width portion 18 is reduced excessively. FIG. 3D illustrates a relation between a curvature radius and the excessive loss of the curved waveguide 11. As illustrated in FIG. 3D, the excessive loss is restrained even if the width of the small width portion 18 is small, when the curvature radius is large. However, the excessive loss increases rapidly when the curvature radius is less than 4 mm. The smaller the width of the small width portion 18 is, the larger the excessive loss is. It is therefore preferable that the curvature radius of the curved waveguide 11 is 4 mm or more.

[Modified Embodiment 1-1]

[0026] FIG. 4A illustrates a structure in accordance with a modified embodiment 1-1. As illustrated in FIG. 4A, the small width portion 18 may be formed so that the width decreases gradually and continuously toward the branch portion 12. That is, the small width portion 18 may have a tapered shape. In this case, scattering loss caused by the changing of the waveguide width is restrained. As illustrated in FIG. 4B, a split part of the branch portion 12 may not have a sharp angle. For example, the split portion of the branch portion 12 has a shape in which a cutout having a width G is formed. In this case, optical property and manufacturability of an optical waveguide may be stabilized. Other branch portions in this description may not have a cutout having the width G.

[Modified Embodiment 1-2]

[0027] FIG. 4C illustrates a structure in accordance with a modified embodiment 1-2. As illustrated in FIG. 4C, the small width portion 18 may be a region in which the waveguide width decreases continuously from an intermediate part of the curved part of the curved waveguide 11. In this case, the scattering loss caused by the changing of the waveguide width is restrained, and the curved waveguide 11 may be downsized more.

[0028] As illustrated in FIG. 3D, the loss is enlarged when the waveguide width is small. It is therefore preferable that the curved waveguide 11 and the small width portion 18 are formed so that the curvature radius increases as the waveguide width decreases. In this case, the loss of the curved waveguide 11 may be restrained, and the curved waveguide 11 may be downsized more.

[0029] In the example of FIG. 4B, the waveguide width decreases gradually from the intermediate part of the curved part of the curved waveguide 11. Therefore, the curvature radius increases as the waveguide width gets smaller. It is preferable that the start point of the small

width portion 18 is positioned on the side of the branch portion 12 compared to a turning point A where a curving direction of the curved waveguide 11 is switched, when the wavelength dependency of loss is enlarged.

[Modified Embodiment 1-3]

[0030] There is a case where a center of a mode distribution is shifted from a center axis of the waveguide in the curved waveguide. The smaller the waveguide width is, the larger the shifting amount is. Therefore, there is a case where the axis shifting at a coupling position of the curved waveguide 11 and the branch portion 12 cause a loss. And so, the center axis of the waveguide may have an off-set on any position of the small width portion 18. A direction of the off-set may be determined according to an excitation mode, a length of a curved waveguide, a width of a curved waveguide, a curvature radius of a curved waveguide or the like.

[0031] FIG. 5A illustrates a structure in accordance with a modified embodiment 1-3. As illustrated in FIG. 5A, the center axis of the waveguide may have an off-set at the start point of the small width portion 18 of the structure of FIG. 4A. In the example of FIG. 5A, the center axis of the small width portion 18 is shifted to a curving direction of the curved waveguide 11. In this case, the loss caused by the axis shifting is restrained.

[Modified Embodiment 1-4]

[0032] FIG. 5B illustrates a structure in accordance with a modified embodiment 1-4. As illustrated in FIG. 5B, the center axis of the waveguide may have an off-set at an end point of the small width portion 18 of the structure of FIG. 4B. In this case, the loss caused by the axis shifting is restrained.

[Modified Embodiment 1-5]

[0033] FIG. 6A illustrates a structure in accordance with a modified embodiment 1-5. When the waveguide width is reduced, a difference of mode diameter between a curved portion and a straight portion is enlarged. In this case, mode mismatch may cause a loss. And so, as illustrated in FIG. 6A, the waveguide width may be reduced discontinuously in the small width portion 18. It is assumed that the width of the start point of the curved waveguide 11 is "w1", the width just before the discontinuously reduced position of the small width portion 18 is "w2", and the width just after the discontinuously reduced position of the small width portion 18 is "w3". In the condition, a relation "w1>w2>w3" may be satisfied. In this case, the loss caused by the mode mismatch is restrained. In the example of FIG. 6A, the center axis has an off-set. However, the center axis may not have the off-set.

[Modified Embodiment 1-6]

[0034] FIG. 6B illustrates a structure in accordance with a modified embodiment 1-6. It is preferable that the small width portion 18 is longer, in order to remove unnecessary mode at an intermediate of the curved waveguide 11. And so, it is preferable that the small width portion 18 extends from an opposite side of the branch portion 12 compared to the turning point A of the curved waveguide 11 to the branch portion 12, when the curved waveguide 11 is formed in a S-shape. The waveguide width is reduced at the turning point A of the curved waveguide 11. In this case, the loss caused by the axis shifting of the mode may be enlarged. And so, the center axis of the waveguide may have an off-set at the turning point A as illustrated in FIG. 6B.

[Modified Embodiment 1-7]

[0035] FIG. 6C illustrates a structure in accordance with a modified embodiment 1-7. As illustrated in FIG. 6C, a width of the branched waveguides of the branch portion 12 may increase gradually or in steps from the curved waveguide 11 side toward the opposite side. In this case, the width of the branched waveguides of the branch portion 12 is smaller than that of the intermediate waveguides 13 and 14 (the interaction portion). Therefore, generation of unnecessary mode after the branching is restrained, and degradation of modulation efficiency of the interaction portion is restrained. It is preferable that the width of the two branched waveguides of the branch portion 12 is changed at the same ratio in the propagation direction in order to move the branching ratio of the branch portion 12 closer to 50%.

[0036] In the above embodiments, the small width portion 18 acting as a low refraction index portion is positioned before the interaction portion. However, the small width portion 18 may be positioned after the interaction portion. In concrete, the small width portion 18 may be formed in a waveguide extending from an end of the curved waveguide 16 on an opposite side of the combine portion 15 to the combine portion 15. In this case, the combine portion 15 acts as a branch portion that is coupled to a curved waveguide and branches. An outputting portion of the curved waveguide 16 acts as a start point of a curved waveguide on an opposite side of a branch portion.

[Second Embodiment]

[0037] A description will be given of a QPSK (Quadrature Phase Shift Keying) modulator in a second embodiment. FIG. 7A illustrates a schematic plane view of a QPSK optical modulator 100a in accordance with a second embodiment. As illustrated in FIG. 7A, the QPSK optical modulator 100a has an electrooptical substrate including two Mach-Zehnder modulators (a first Mach-Zehnder modulator and a second Mach-Zehnder modu-

lator). At least one of the first Mach-Zehnder optical modulator and the second Mach-Zehnder optical modulator has the same structure as the Mach-Zehnder optical modulator 100 in accordance with the first embodiment.

[0038] The first Mach-Zehnder optical modulator has a curved waveguide 11a, a branch portion 12a, intermediate waveguides 13a and 14a, a combine portion 15a and a curved waveguide 16a. The second Mach-Zehnder optical modulator has a curved waveguide 11b, a branch portion 12b, intermediate waveguides 13b and 14b, a combine portion 15b and a curved waveguide 16b.

[0039] The QPSK optical modulator 100a has a branch portion 19 at a light-incoming end and a combine portion 20 at a light-outputting end. The curved waveguide 11a and the curved waveguide 11b branch at the branch portion 19. The curved waveguide 16a and the curved waveguide 16b combine at the combine portion 20.

[0040] FIG. 7B illustrates an enlarged view of the branch portion 19, the curved waveguides 11a and 11b and the branch portions 12a and 12b. In an example of FIG. 7B, a small width portion 18a is provided in a waveguide extending from a start point of the curved waveguide 11a to the branch portion 12a, and a small width portion 18b is provided in a waveguide extending from a start point of the curved waveguide 11b to the branch portion 12b. In this case, the degradation of the branching ratio is restrained in both of the branch portions 12a and 12b.

[0041] FIG. 8 illustrates another example of the curved waveguides 11a and 11b and the branch portions 12a and 12b. In an example of FIG. 8, the branch portion 12a and the branch portion 12b may be located at different position in a longitudinal direction (propagation direction) of the QPSK optical modulator 100a. In this case, the curved waveguide 11a and the curved waveguide 11b may have a different curvature radius, a different angle or the like. Thus, the shape of the small width portions 18a and 18b may be determined separately.

[0042] For example, the length of the small width portion 18a in the propagation direction may be different from that of the small width portion 18b. The width of the small width portion 18a may be different from that of the small width portion 18b. When the center axis of the small width portions 18a and 18b has an off-set, the off-set amount of the small width portion 18a may be different from that of the small width portion 18b. The width of a start point of the branch portion 12a may be different from that of the branch portion 12b. Coupling loss of each waveguide may be reduced when each parameter is optimized.

[Third Embodiment]

[0043] A description will be given of a "m" X "n" optical coupler in a third embodiment. As an example, an optical coupler in accordance with the third embodiment is 2 X 2 optical coupler. FIG. 9A illustrates a schematic plane view of an optical coupler 40 in accordance with the third

embodiment. As illustrated in FIG. 9A, the optical coupler 40 has two inputting waveguides 41 and 42 and two outputting waveguides 43 and 44. At least one of the inputting waveguides 41 and 42 and the outputting waveguides 43 and 44 has the curved waveguide 11 and the small width portion 18 in accordance with the first embodiment. The optical coupler 40 acts as the branch portion 12 in accordance with the first embodiment.

[0044] In the example of FIG. 9A, the inputting waveguide 41 includes the curved waveguide 11 and the small width portion 18. In the example of FIG. 9A, the small width portion 18 is provided in a waveguide extending from the start point of the curved waveguide 11 to the optical coupler 40. In this case, degradation of a branching ratio of a light from the inputting waveguide 41 is restrained. The preferable branching ratio may not be limited to 50% in the optical coupler 40, and may be set to be a desirable one required for the optical coupler 40.

[0045] As illustrated in FIG. 9B, the small width portion may be provided in all of the inputting waveguides 41 and 42 and the outputting waveguides 43 and 44. Each width may decrease toward the optical coupler 40 with the same ratio in at least two of the waveguides. In this case, the loss and the wavelength dependency of the two waveguides may be equal to each other. Variation of a loss difference between the two waveguides at the designing and at the manufacturing may be restrained. Thus, an extinction ration having small production tolerance in a wide wavelength range may be obtained. From the viewpoint, two waveguides coupled to the optical coupler 40 from the same side may be symmetrically located with respect to the center axis of the optical coupler 40.

[0046] As illustrated in FIG. 9C, the waveguide width on the side of the optical coupler 40 may be larger than that of the small width portion 18. In this case, the coupling loss caused by extended mode field caused by the small waveguide width is restrained.

[0047] In the above embodiments, the effective refraction index is reduced by reducing the waveguide width. FIG. 10A through FIG. 10C illustrate another adjusting method of the effective refraction index. As mentioned above, the effective refraction index may be adjusted based on a cross sectional area of a waveguide, a width of a waveguide, a depth of a waveguide, impurity concentration of a waveguide and so on.

[0048] The effective refraction index may be reduced by reducing the cross sectional area of a waveguide. In concrete, as illustrated in FIG. 10A, when a relation "a waveguide width $w_b < a$ waveguide width w_a " is satisfied, an effective refraction index of a waveguide having the waveguide width w_b is smaller than that of a waveguide having the waveguide width w_a . As illustrated in FIG. 10B, when a relation "a waveguide depth $d_2 < a$ waveguide depth d_1 " is satisfied, an effective refraction index of a waveguide having the waveguide depth d_2 is smaller than that of a waveguide having the waveguide depth d_1 .

[0049] As illustrated in FIG. 10C, a relation "impurity

concentration n_2 of a waveguide $<$ impurity concentration n_1 " is satisfied, an effective refraction index of a waveguide having the impurity concentration n_2 is smaller than that of a waveguide having the impurity concentration n_1 .

[0050] The structure of the waveguide is not limited to the above examples. As another example, a silicon waveguide may be used. FIG. 11 illustrates cross sectional view of a silicon waveguide. As illustrated in FIG. 11, the silicon waveguide may have a lower cladding layer 60 and an upper cladding layer 70 on a silicon substrate 50. An optical waveguide 80 may be formed in the lower cladding layer 60. For example, a silica glass may be used as the lower cladding layer 60 and the upper cladding layer 70. The optical waveguide 80 may be formed by injecting Ge or the like into the lower cladding layer 60 with a solid-phase diffusion method, an ion-plating method or the like. The above embodiments may be used in the silicon waveguide.

[0051] In the above embodiments, a S-shaped curved waveguide is used as a curved waveguide. However a structure is not limited to the above structure. The coupling between the curved waveguide and the branch portion causes the shifting of the branching ratio of the branch portion. Therefore, a curved waveguide curving toward only a single direction may be used in the above embodiments.

[Fourth Embodiment]

[0052] FIG. 12 illustrates a block diagram of an optical transmitter 200 in accordance with a fourth embodiment. As illustrated in FIG. 12, the optical transmitter 200 has an optical device 210, a data generation portion 220 and so on. The optical device 210 is a semiconductor laser or the like having any one of the above-mentioned optical modulators. The data generation portion 220 transmits a drive signal for driving the optical device 210 to the optical device 210. The optical device 210 outputs an optical modulation signal according to the drive signal from the data generation portion 220. The optical modulation signal is output outside through an optical fiber or the like. An optical modulator mounted on the optical device 210 may be downsized and may have a high extinction ratio. Therefore, the optical transmitter 200 may output a high property optical signal.

[0053] The present disclosure also extends to the subject-matter defined by the following sequence of 15 numbered clauses.

[0054] Clauses:

1. An optical waveguide formed in a substrate comprising: a curved waveguide; and a branch portion that is coupled to the curved waveguide and branches, wherein a low refraction index portion having an effective refraction index that is lower than that of a start point of the curved waveguide on an opposite

side of the branch portion is provided in a waveguide extending from the start point of the curved waveguide to the branch portion.

2. The optical waveguide as claimed in clause 1, wherein the effective refraction index of the low refraction index portion decreases continuously or in steps toward the branch portion. 5

3. The optical waveguide as claimed in clause 1 or 2, wherein the low refraction index portion is provided at an intermediate of the curved waveguide. 10

4. The optical waveguide as claimed in clause 3, wherein a curvature radius of the curved waveguide is 4mm or more. 15

5. The optical waveguide as claimed in clause 3 or 4, wherein the curvature radius of the low refraction index portion increases as the effective refraction index decreases. 20

6. The optical waveguide as claimed in any of clauses 1 to 5, wherein a center axis of a waveguide has an off-set in the low refraction index portion. 25

7. The optical waveguide as claimed in any of clauses 1 to 6, wherein:

the curved waveguide is a S-shaped curved waveguide; and the start point of the low refraction index portion on the opposite side of the branch portion is positioned on an opposite side of the branch portion compared to a turning point where a curving direction of the curved waveguide is switched, in the curved waveguide. 30 35

8. The optical waveguide as claimed in clause 7, wherein a center axis of a waveguide has an off-set at the turning point of the curved waveguide. 40

9. The optical waveguide as claimed in any of clauses 1 to 6, wherein:

the curved waveguide is a S-shaped curved waveguide; and the start point of the low refraction index portion on the opposite side of the branch portion is positioned on the side of the branch portion compared to a turning point where a curving direction of the curved waveguide is switched, in the curved waveguide. 45 50

10. The optical waveguide as claimed in any of clauses 1 to 9, wherein an effective refraction index of each branched waveguide of the branch portion increases gradually or in steps toward an opposite side 55

from a branching point.

11. The optical waveguide as claimed in clause 10, wherein an effective refraction index of each branched waveguide is changed with the same ratio in an optical propagation direction.

12. The optical waveguide as claimed in any of clauses 1 to 11, wherein the low refraction index portion has relatively small effective refraction index by having a cross sectional area that is lower than that of the start point of the curved waveguide.

13. The optical waveguide as claimed in any of clauses 1 to 11, wherein the low refraction index portion has relatively small effective refraction index by having a width that is smaller than that of the start point of the curved waveguide.

14. An optical modulator of Mach-Zehnder type comprising:

a first branch portion of light-inputting side; and a second branch portion of light-outputting side, wherein:

at least one of the first branch portion and the second branch portion includes an optical waveguide formed in a substrate comprising a curved waveguide and a branch portion that is coupled to the curved waveguide and branches;

a low refraction index portion having an effective refraction index that is lower than that of a start point of the curved waveguide on an opposite side of the branch portion is provided in a waveguide extending from the start point of the curved waveguide to the branch portion; and the substrate has electrooptical effect.

15. An optical coupler comprising:

an inputting waveguide; and an outputting waveguide, wherein:

at least one of the inputting waveguide and the outputting waveguide includes an optical waveguide formed in a substrate comprising a curved waveguide and a branch portion that is coupled to the curved waveguide and branches; and

a low refraction index portion having an effective refraction index that is lower than that of a start point of the curved waveguide on an opposite side of the branch portion is provided in a waveguide extending from the

start point of the curved waveguide to the branch portion.

Claims

1. An optical waveguide formed in a substrate comprising:

a curved waveguide (11, 16) having a first end and a second end; and
a branch portion (12, 15) that is coupled to the second end of the curved waveguide (11, 16) and branches,
wherein the curved waveguide (11, 16) comprises a low refraction index portion (18) having an effective refraction index that is lower than that of the rest of the curved waveguide (11, 16), / the low refraction index portion (18) is provided from an intermediate part of the curved waveguide (11, 16) between the first end and the second end of the curved waveguide (11, 16).

2. The optical waveguide as claimed in claim 1, wherein the effective refraction index of the low refraction index portion decreases continuously or in steps toward the branch portion.

3. The optical waveguide as claimed in claim 1 or 2, wherein the low refraction index portion is provided at an intermediate of the curved waveguide.

4. The optical waveguide as claimed in claim 3, wherein a curvature radius of the curved waveguide is 4mm or more.

5. The optical waveguide as claimed in claim 3 or 4, wherein the curvature radius of the low refraction index portion increases as the effective refraction index decreases.

6. The optical waveguide as claimed in any of claims 1 to 5, wherein a center axis of a waveguide has an off-set in the low refraction index portion.

7. The optical waveguide as claimed in any of claims 1 to 6, wherein:

the curved waveguide is a S-shaped curved waveguide; and the start point of the low refraction index portion on the opposite side of the branch portion is positioned on an opposite side of the branch portion compared to a turning point where a curving direction of the curved waveguide is switched, in the curved waveguide.

8. The optical waveguide as claimed in claim 7, wherein a center axis of a waveguide has an off-set at the turning point of the curved waveguide.

9. The optical waveguide as claimed in any of claims 1 to 6, wherein:

the curved waveguide is a S-shaped curved waveguide; and the start point of the low refraction index portion on the opposite side of the branch portion is positioned on the side of the branch portion compared to a turning point where a curving direction of the curved waveguide is switched, in the curved waveguide.

10. The optical waveguide as claimed in any of claims 1 to 9, wherein an effective refraction index of each branched waveguide of the branch portion increases gradually or in steps toward an opposite side from a branching point.

11. The optical waveguide as claimed in claim 10, wherein an effective refraction index of each branched waveguide is changed with the same ratio in an optical propagation direction.

12. The optical waveguide as claimed in any of claims 1 to 11, wherein the low refraction index portion has relatively small effective refraction index by having a cross sectional area that is lower than that of the start point of the curved waveguide.

13. The optical waveguide as claimed in any of claims 1 to 11, wherein the low refraction index portion has relatively small effective refraction index by having a width that is smaller than that of the start point of the curved waveguide.

14. An optical modulator of Mach-Zehnder type comprising:

a first branch portion of light-inputting side; and a second branch portion of light-outputting side, wherein:

at least one of the first branch portion and the second branch portion includes an optical waveguide formed in a substrate according to any of Claims 1-13; and the substrate has electrooptical effect.

15. An optical coupler comprising:

an inputting waveguide; and an outputting waveguide, wherein:

at least one of the inputting waveguide and the outputting waveguide includes an optical waveguide formed in a substrate according to any of Claims 1-13.

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FIG. 1A

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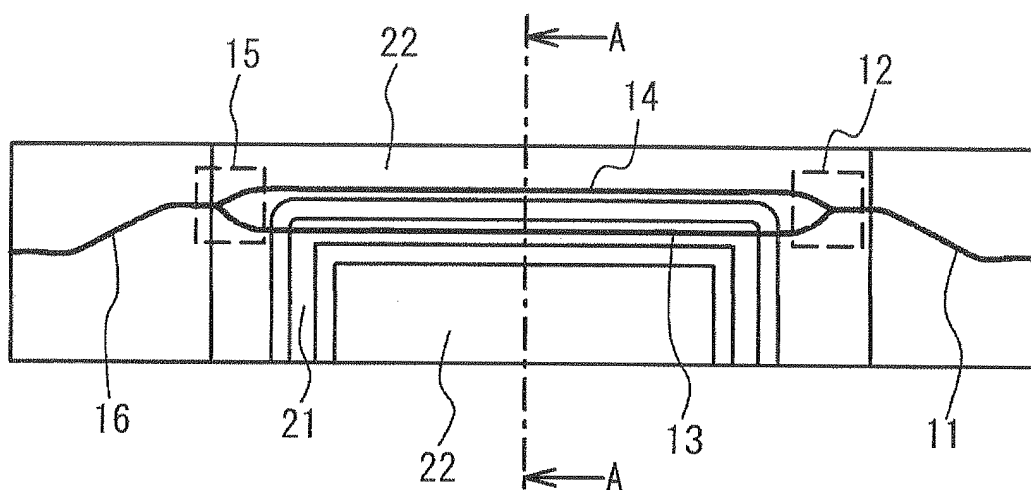


FIG. 1B

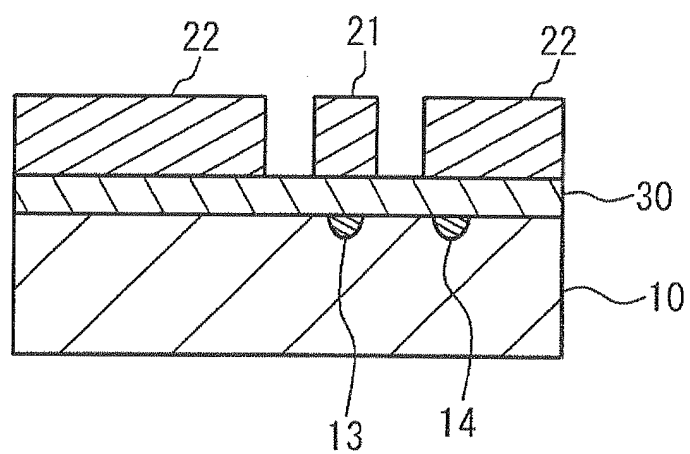


FIG. 2A

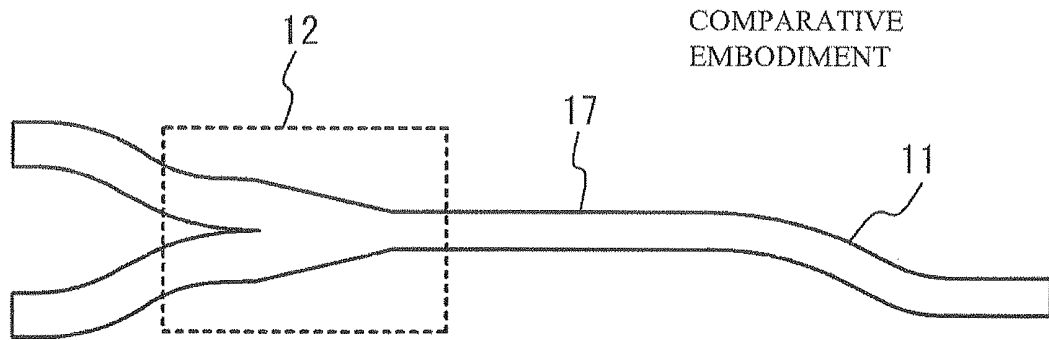


FIG. 2B

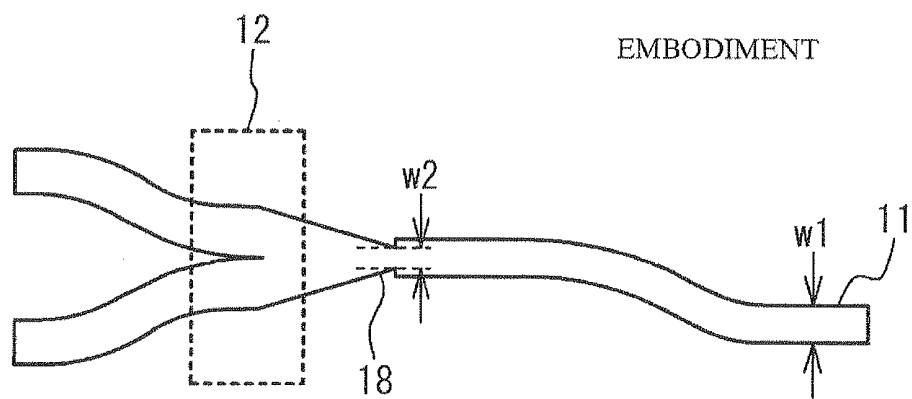


FIG. 3A

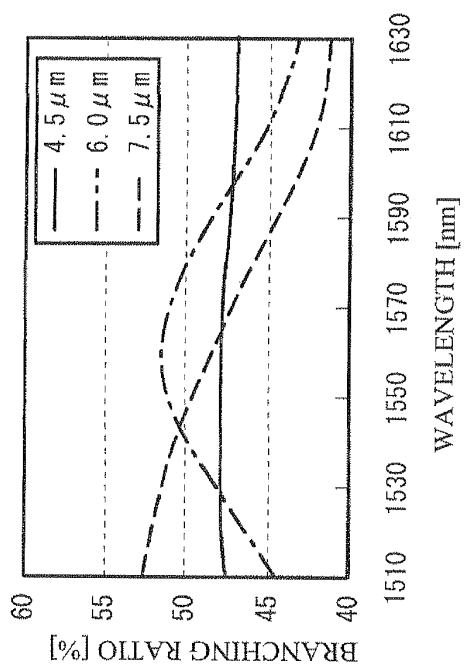


FIG. 3B

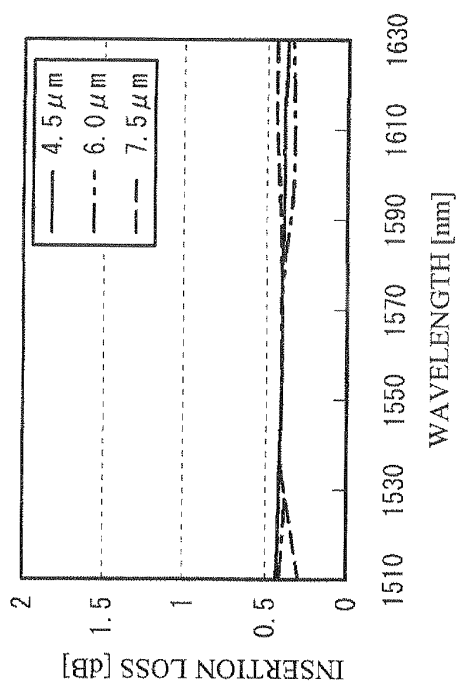


FIG. 3C

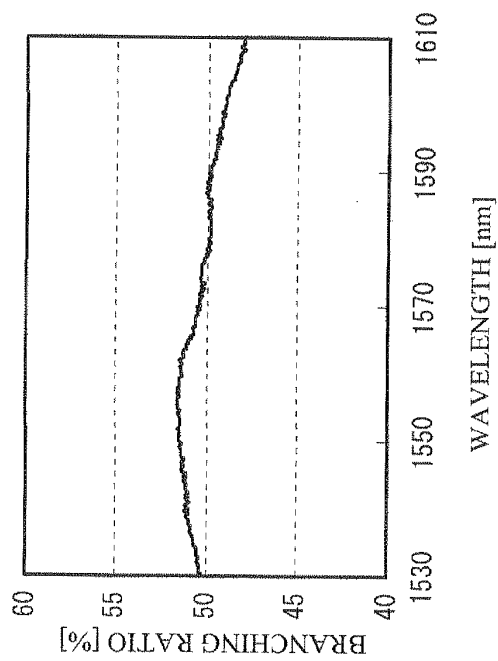


FIG. 3D

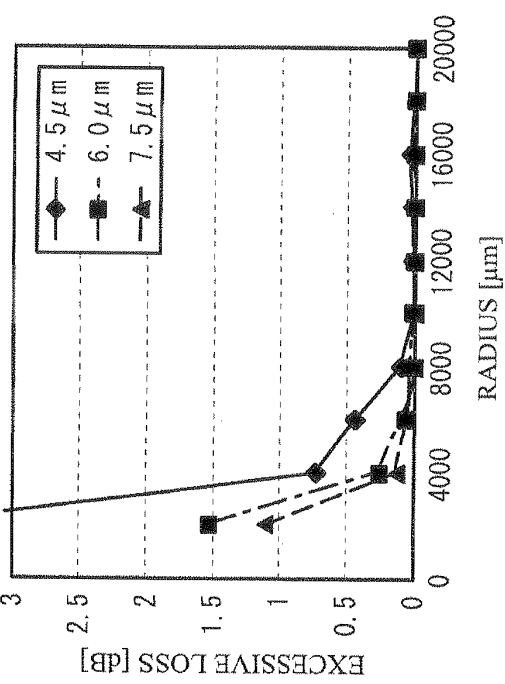


FIG. 4A

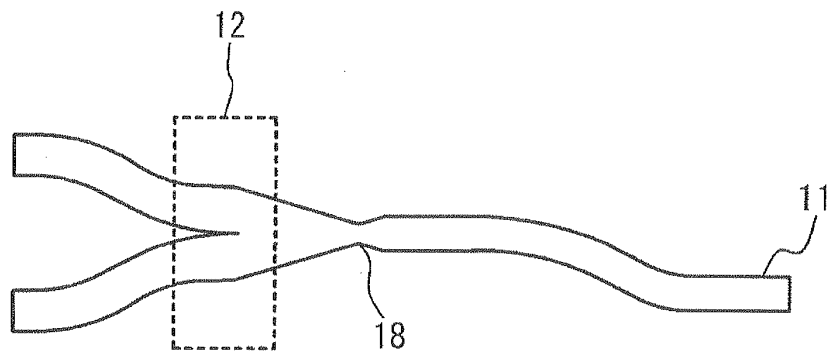


FIG. 4B

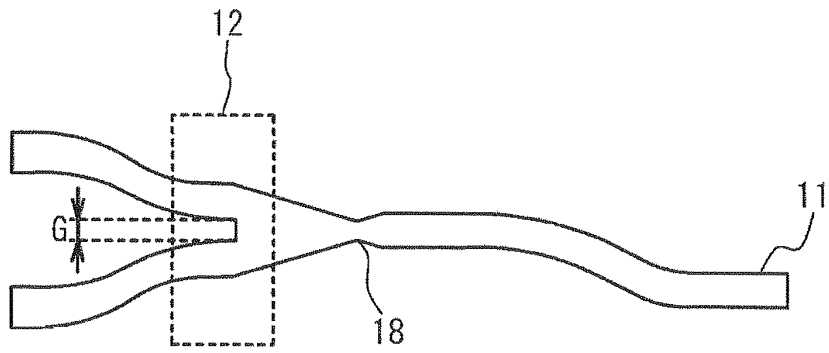


FIG. 4C

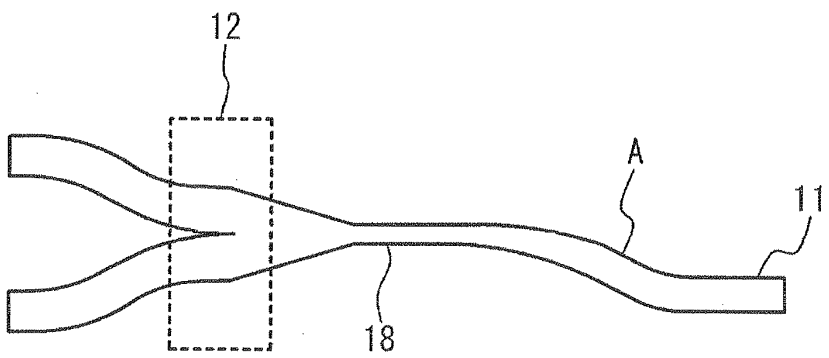


FIG. 5A

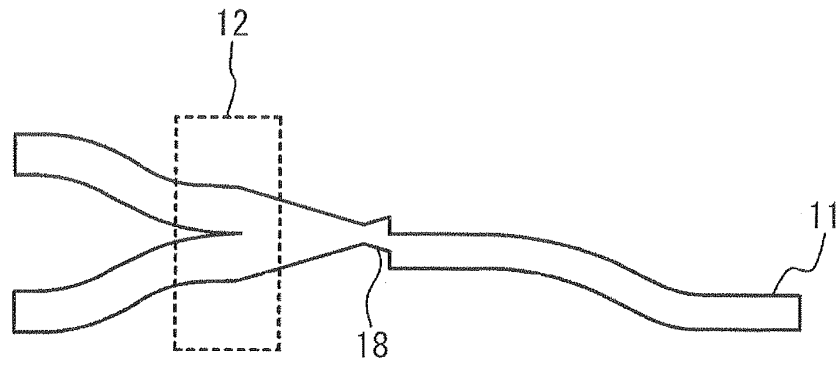


FIG. 5B

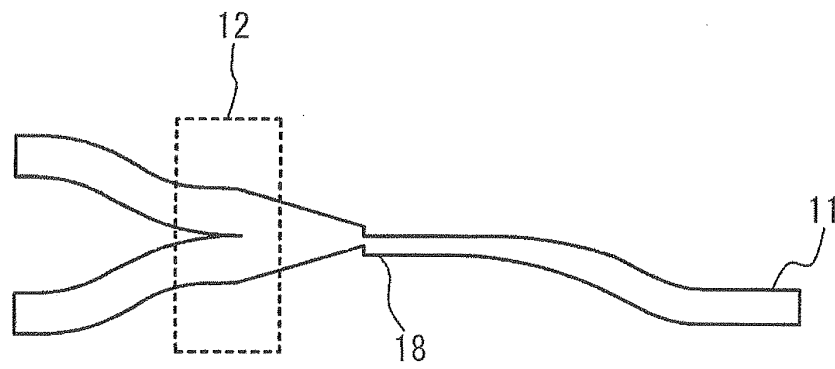


FIG. 6A

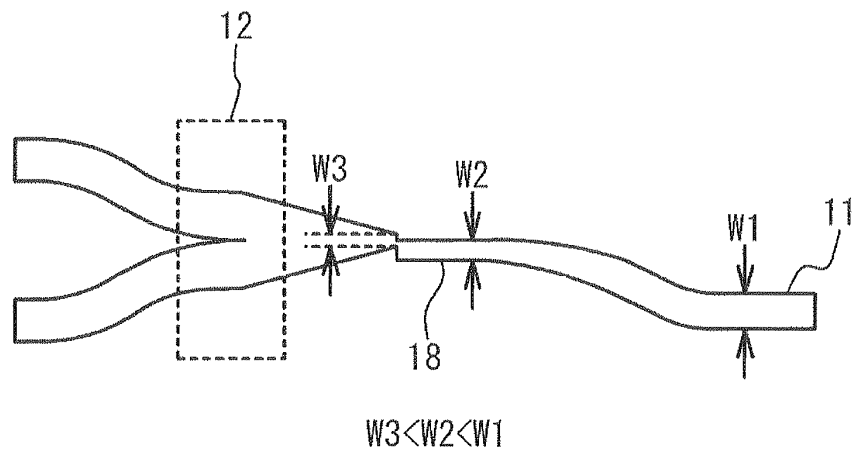


FIG. 6B

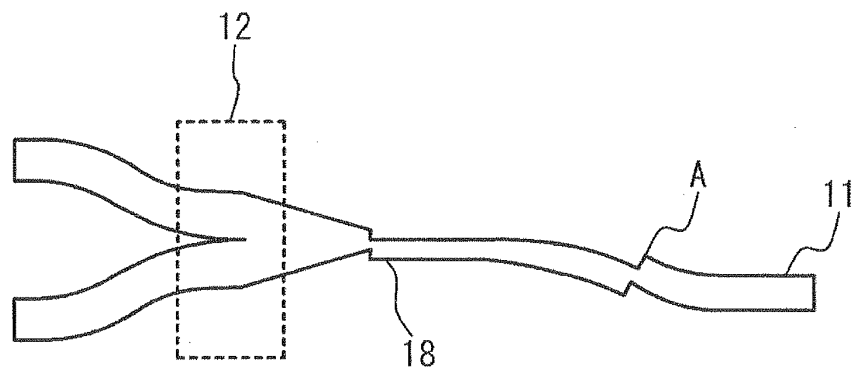


FIG. 6C

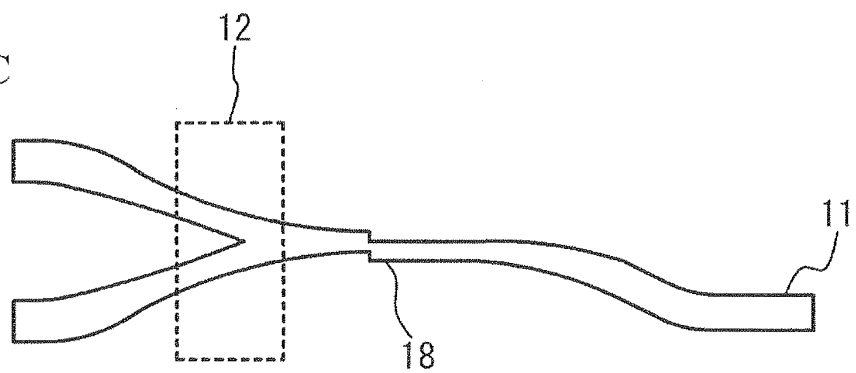


FIG. 7A

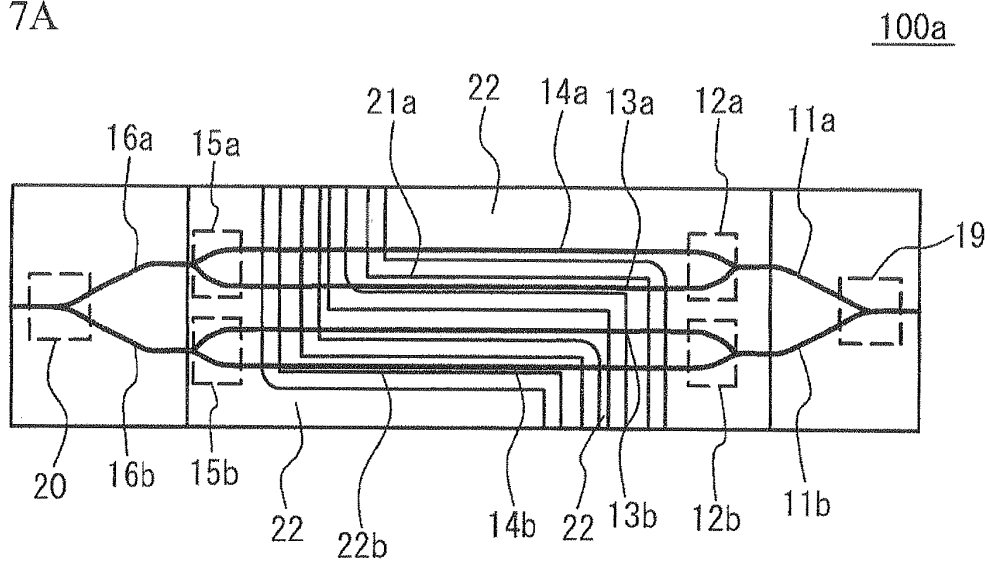


FIG. 7B

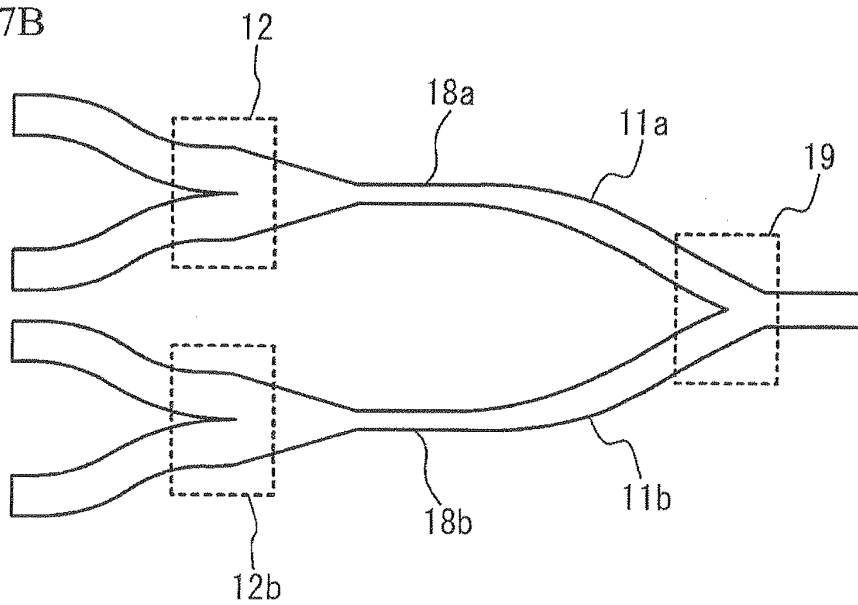


FIG. 8

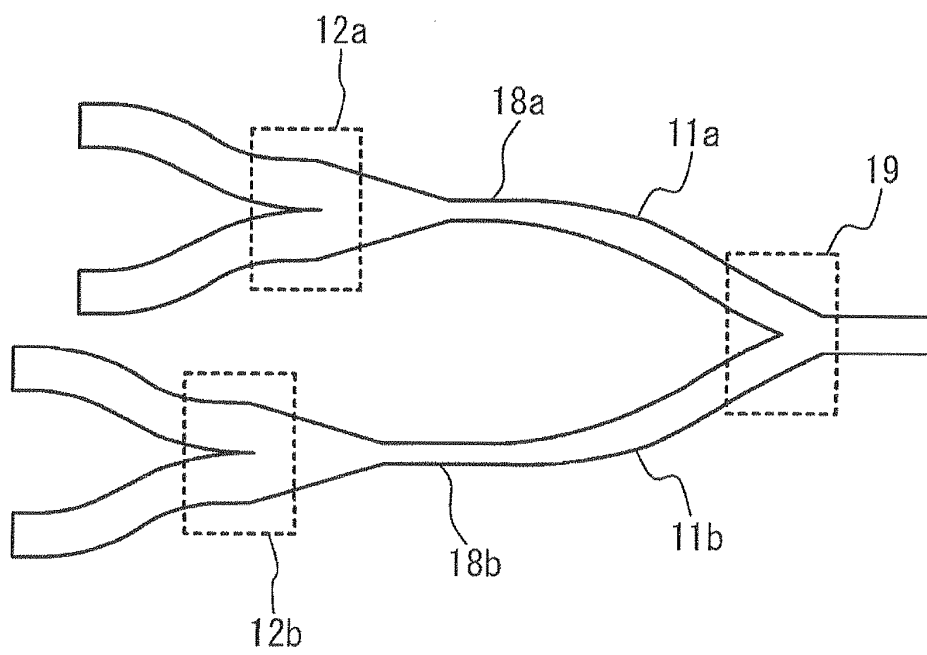


FIG. 9A

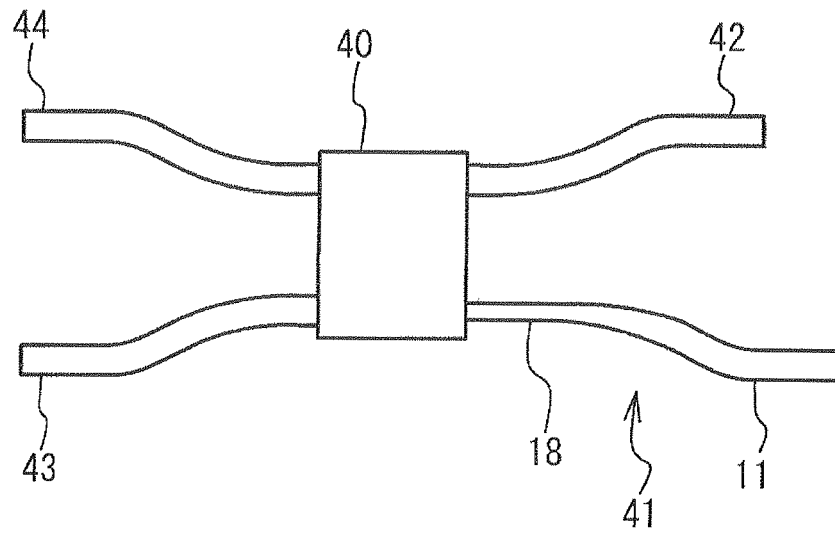


FIG. 9B

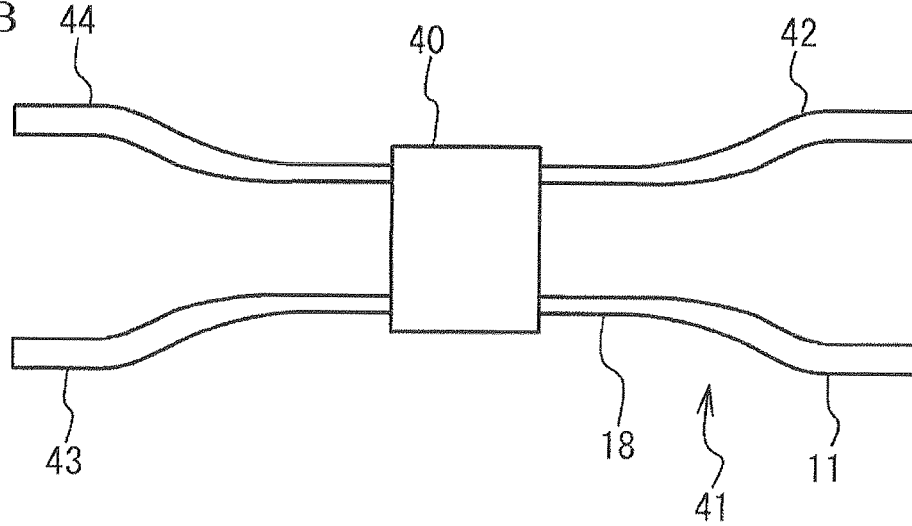


FIG. 9C

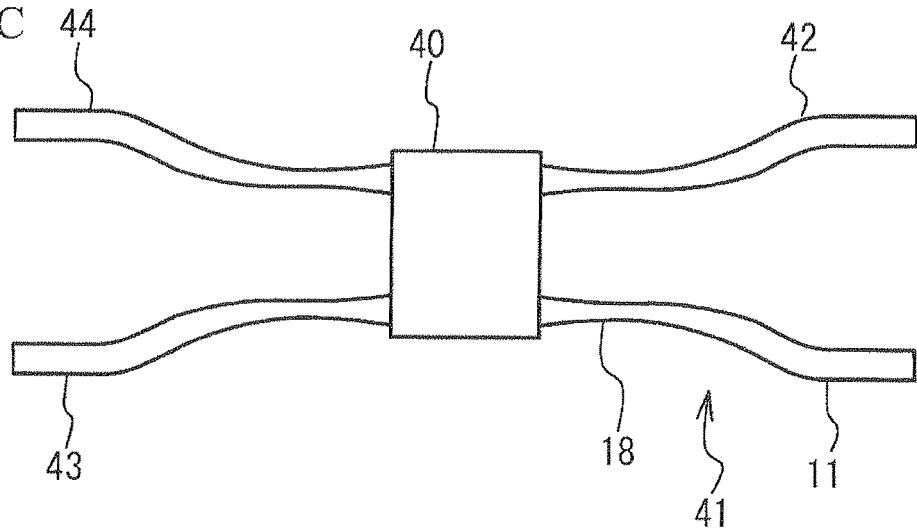


FIG. 10A

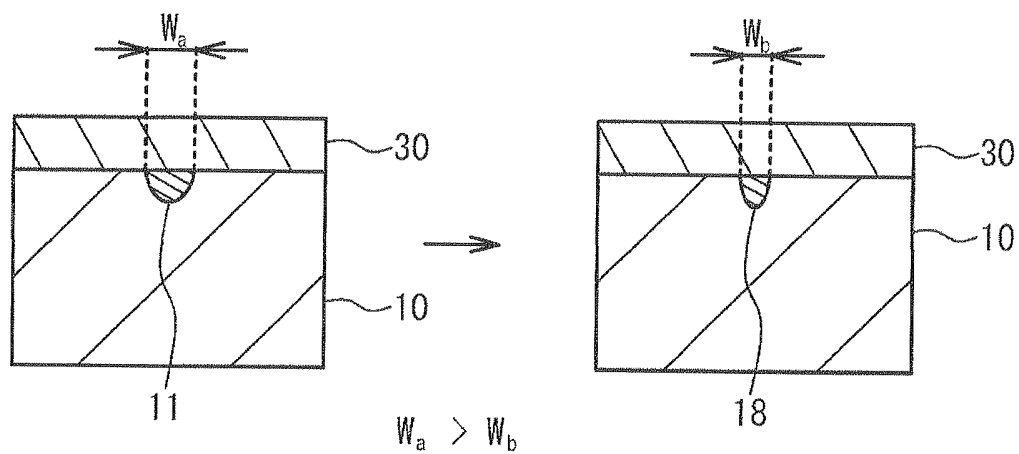


FIG. 10B

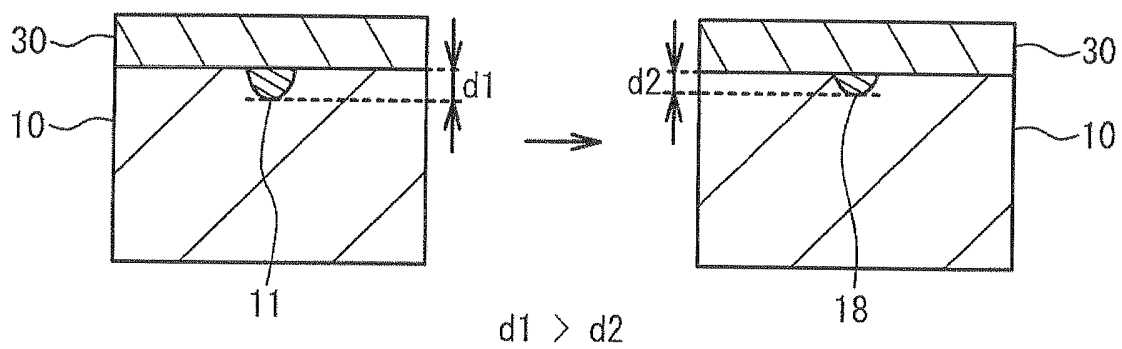


FIG. 10C

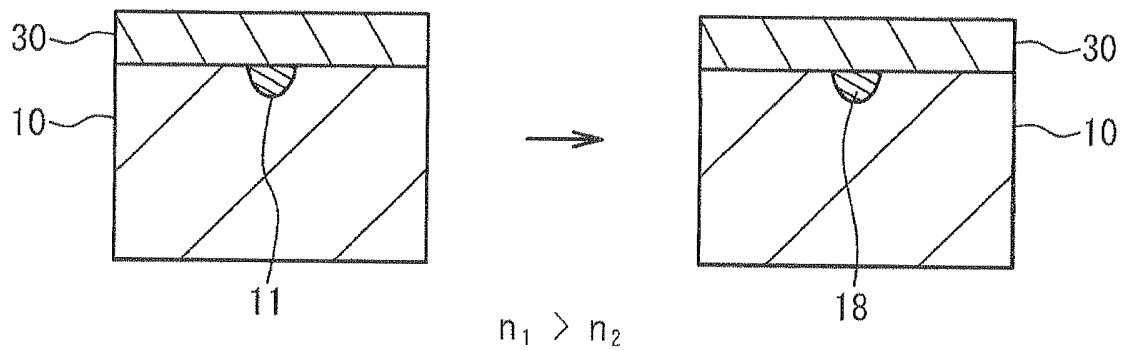


FIG. 11

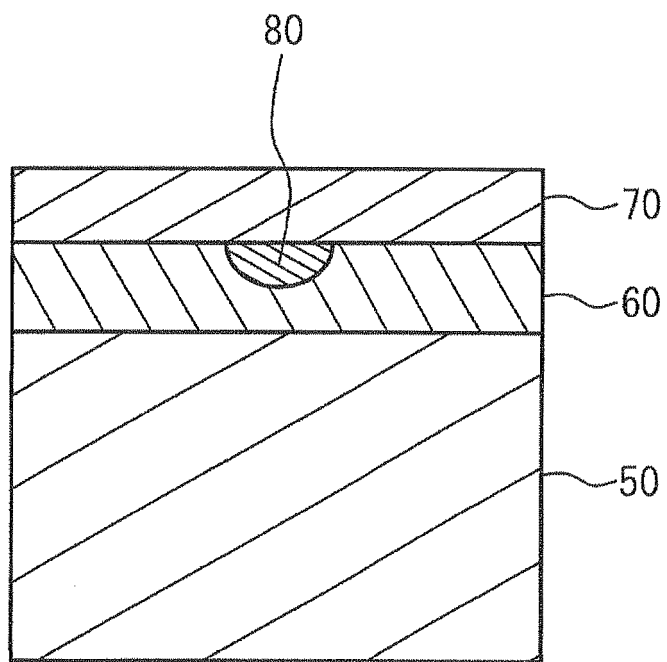
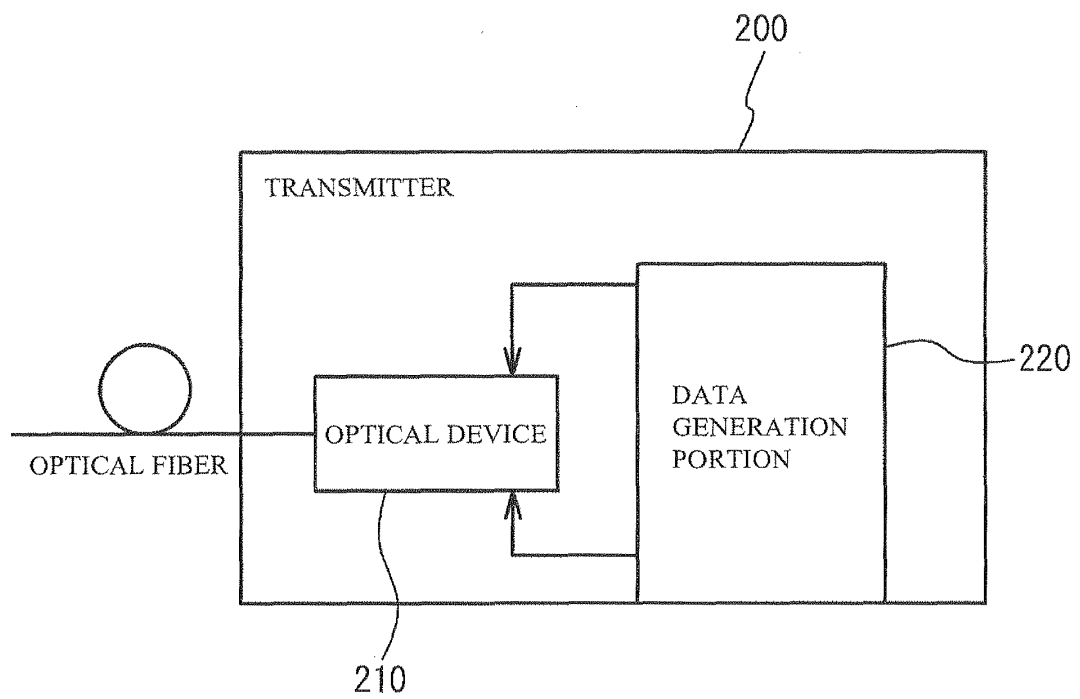


FIG. 12





EUROPEAN SEARCH REPORT

Application Number
EP 13 17 1823

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Y	* abstract * * paragraph [0020]; figures 2-3 * * paragraph [0021]; figures 5-6 * * paragraph [0025]; figure 7 * * paragraphs [0026] - [0029]; figures 8,9 *	10,11,14	G02F1/313 G02B6/122 G02B6/125
Y	----- TSUTOMU KITO ET AL: "BENDING LOSS REDUCTION IN SILICA-BASED WAVEGUIDES BY USING LATERAL OFFSETS", JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 13, no. 4, 1 April 1995 (1995-04-01), pages 555-562, XP000513569, IEEE SERVICE CENTER, NEW YORK, NY, US ISSN: 0733-8724, DOI: 10.1109/50.372465 * the whole document *	14	
X	----- EP 0 651 268 A1 (SUMITOMO ELECTRIC INDUSTRIES [JP]) 3 May 1995 (1995-05-03) * column 63, line 57 - column 67, line 9; figures 39-40 *	15	TECHNICAL FIELDS SEARCHED (IPC)
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A	----- A. W. Snyder and J. D. Love: "Optical Waveguide Theory", 1983, Chapman and Hall, XP002701135, ISBN: 0-412-09950-0 pages 482-485,1pp, * page 482 - page 485 *	5	
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 11 July 2013	Examiner Cossu, Alessandro
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3
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**ANNEX TO THE EUROPEAN SEARCH REPORT
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EP 13 17 1823

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